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Modeling and control of Type-2 wind turbines for sub-synchronous resonance damping

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ABSTRACT

The rapid increase of wind power penetration into power systems around the world has led transmission system operators to enforce stringent grid codes requiring novel functionalities from renewable energy-based power generation. For this reason, there exists a need to asses whether wind turbines (WTs) will comply with such functionalities to ensure power system stability. This paper demonstrates that Type-2 WTs may induce sub-synchronous resonance (SSR) events when connected to a series-compensated transmission line, and with proper control, they may also suppress such events. The paper presents a complete dynamic model tailored to study, via eigenanalysis, SSR events in the presence of Type-2 WTs, and a systematic procedure to design a power system stabilizer using only local and measurable signals. Results are validated through a case study based on the IEEE first benchmark model for SSR studies, as well as with transient computer simulations.

1. Introduction

Wind power is becoming an increasingly popular form of renewable energy around the world. The total wind power amount installed worldwide is currently more than 336 GW. According to a World Wind Energy Association report [1], Asia accounts for the largest share of wind power plants (WPPs) with 36.9%, followed by Europe with 36.7% and North America with 20.1%. For many countries wind power has already become an important electricity source, e.g, Denmark with 34% and Portugal, Spain and Ireland with penetration levels around 20%. In the US, the total wind generation installed as of 2013 is more than 61 GW, representing 4.5% of the 2013 electricity demand [2]. Moreover, installation of offshore wind power is growing fast, since there is more constant wind and less space limitation. Due to the rapid increase of wind power penetration into the electricity production share and the pertinent reduction of power system inertia, transmission systems operators (TSOs) have developed restrictive grid codes for renewable energies. For example, WPPs must provide various ancillary services (frequency regulation [3], fault ride-through [4], among others [5]) as conventional synchronous generators do. Renewable energies with large grid integration such as photovoltaic and wind power, must thus be capable to provide ancillary services such as power oscillation damping [6,7], sub-synchronous resonance (SSR) mitigation [8] and synthetic inertia. Some of them are currently being provided by conventional generation or flexible ac transmission systems (FACTS) [9–11]. It is worth noting that the Spanish TSO and the European agency ENTSO-E have developed new drafts of the current grid codes where such concepts are already being referred [12,13].

Some authors have already investigated the torsional dynamics of wind turbines (WTs) [14,15], and the potential contribution of WPPs to damp power oscillations [16,17]. However, these studies mainly focus on variable-speed WTs (i.e., Type-3 and Type-4). Type-3 and 4 WTs are equipped with a voltage source converter (VSC), and therefore their control scheme can easily be augmented to emulate FACTS control capabilities to damp power oscillations. Under the rubric of power system stabilizers (PSS) [18], a significant number of control schemes have been proposed for this purpose and some of them are already present in the field [19]. PSS functionalities based on artificial intelligence, H_∞, or adaptive/predictive control have been utilized to augment the VSC's control scheme of Type-3 and 4 WTs, all featuring acceptable performance

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[19–21]. On the other hand, Type-2 WTs-based on a wound rotor induction generator (WRIG)-rely on a more modest power converter, namely, a rotor external resistor controlled by a simple dc chopper, and as a result have traditionally been perceived as less capable to provide ancillary services for power oscillations damping. Although the popularity of Type-2 WTs is decreasing within the wind power industry, they are still present on the market and on the grid [22]. Because of this, it is of interest to study whether they could induce SSR, as well as their capability to support power system stability.

Potential contribution of Type-2 WTs to mitigate torsional SSR events occurring as a result of the interaction of conventional synchronous generators and series-compensated transmission lines have already been analyzed by the authors of this paper in [8,24]. However, since a sub-synchronous oscillation was detected taking place among Type-3 WTs and a series-compensated line [17,21], it is of interest to analyze whether Type-2 WTs may also engage in SSR events. This is the subject of this paper. The paper demonstrates that indeed Type-2 WTs can induce SSR events in series-compensated transmission lines under large levels of series compensation. The paper provides the theoretical foundations via eigenanalysis for the occurrence of SSR events, utilizing a modified version of the IEEE first benchmark model (IEEE-FBM) for SSR studies [23]. Furthermore, the paper provides a systematic design procedure to augment a Type-2 WT dc chopper control scheme with a PSS to effectively suppress SSR events. Fig. 1 shows the power system to be studied, highlighting the modification to the IEEE-FBM.

The paper is organized as follows. Section 2 presents an overview of SSR events and their implications to the stability of a power system. Detailed modeling of the various system components is discussed in Section 3. Section 4 provides a systematic approach to tune a PSS tailored to SSR damping. The computer simulations of Section 5 validate the approach and the conclusions of Section 6 close the paper.

2. Sub-synchronous resonance

According to the IEEE SSR Working Group, a SSR event corresponds to an oscillation between the electric grid and the turbine-generator shaft at frequencies below the synchronous frequency of the grid [25]. These events were first detected at the Mohave power plant in Nevada, U.S.A., in the 1970s [23]. Since then, the SSR phenomenon have been extensively studied to understand, avoid and mitigate in case of occurrence by introducing additional controllers in synchronous power stations. In general, any system capable of exchanging energy at frequencies below the rated frequency is considered a potential source of SSR excitation. The most common case occurs in series-compensated transmission lines, where the interaction between the capacitor's capacitance and the transmission line's inductance introduces a natural frequency of resonance [26].

SSR events are usually classified into two different groups depending on the systems participating in the interaction. They are known as induction generator effect (IGE) and torsional interaction (TI) [18]. IGE can take place when the rotor resistance (which is seen negative because the rotor rotates faster than the magnetic field) is larger than the sum of armature and network resistances at a resonant frequency. This case leads to self-excitation increasing the voltages and currents delivered to the grid. On the other hand, TI related the interaction among electrical and mechanical parts. It occurs when the natural resonant frequencies of the mechanical parts (i.e., turbine and generator shaft) matches or is close to an electrical mode, leading to mechanical failure and shaft damage.

The resonant mode for a lossless series-compensated transmission line, f_n, can be computed using (1),

$$f_n = f_0 \sqrt{\frac{\sum X_C}{\sum X_L}}, \qquad (1)$$

where $\sum X_C$ and $\sum X_L$ represents, respectively, the total capacitive and inductive reactance of the transmission line and f_0 is the nominal system frequency [18]. From (1), the super-synchronous and SSR frequencies (f_r) can be determined by calculating the difference between the synchronous frequency of the system (f_0) and previous resonance mode (f_n) as

$$f_r = f_0 \pm f_n. \qquad (2)$$

The value of f_r provides an approximate idea about the frequencies of resonance that would appear in such power system conditions.

3. System modeling

The power system we consider for SSR analysis is based on a modified version the of the IEEE-FBM as shown in Fig. 1 [23]. The IEEE-FBM model introduced in [23] has been adapted by replacing the generating unit (a conventional synchronous generator) with a WPP based on Type-2 WTs. As illustrated in the figure, a Type-2 WT system corresponds to the aggregation of a wind turbine, a drive train, a WRIG, a power converter, and a shunt capacitor connected at the generator's output terminals. The WPP is modeled by aggregating a number (N) of Type-2 WTs with a two-mass drive train mechanical system. The modeling of electrical components in the subsections below is performed in the $d-q$ reference frame utilizing dynamic phasors (i.e., $\vec{x} = x_d + jx_q$).

3.1. Series-compensated transmission line model

The IEEE-FBM grid can be readily lumped into a series RLC circuit as suggested in Fig. 2. The model is represented by (3) in the $d-q$ reference frame rotating synchronously at ω_s (which is defined as $\omega_s = \omega_{el}/\omega_b$ being ω_{el} and ω_b the electrical frequency

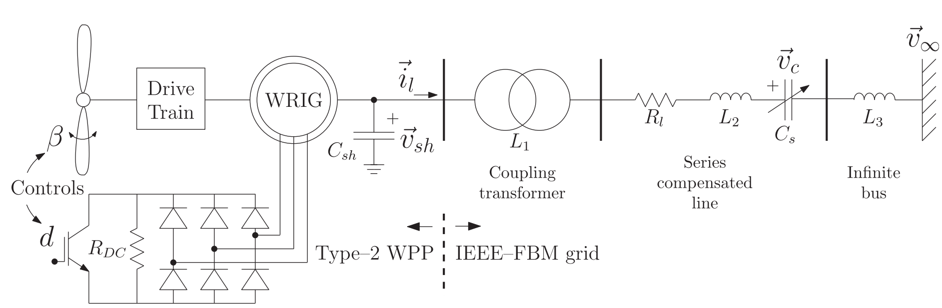

Fig. 1. Schematic of the power system under study. The IEEE-FBM for SSR analysis has been modified replacing the synchronous generator by a Type-2 WPP [23].